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High-volume, ultra-low-density fly ash foamed concrete

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Resource efficiency is a core criterion for the regulation of construction products and rightly promotes the most sustainable solution. This paper reports the development a low embodied carbon dioxide backfill material based on an ultra-low-density foamed concrete using a high volume of fly ash to replace Portland cement. This material builds on previously reported research on the underlying causes of instability in low-density foamed concrete mixes and demonstrates that, with the addition of a small amount of calcium sulfoaluminate (CSA) cement, stable ultra-low-density foamed concretes with density as low as 150 kg/m^3 can be produced. A high volume of fly ash up to 70% of cement phase has been used, which reduced the average bubble size of the foamed concrete and increased the thickness of the bubble walls. The observed microstructure of fly ash foamed concretes was improved over the long term. The use of fly ash significantly reduced the embodied carbon dioxide of these mixes, which potentially has significant benefits for large-scale backfill and similar applications.

Introduction

The need for resource-efficient bulk materials is well established and is a core requirement of the construction products regulation (CPR) (EP and CEU, 2011), which promotes the most sustainable solution. Combined with world atmospheric carbon dioxide (CO_2) breaching 400 ppm in 2016 (NOAA, 2016), minimising the embodied carbon dioxide (eCO_2) through the use of secondary materials, as well as energy-efficient construction activities, without compromising performance, is of vital importance for contemporary design and construction practice.

The development of most sites often requires some form of infill or backfill, which most commonly uses high-quality primary aggregate such as 'Type 1 or 2' (Highways England, 2016) and in some locations recycled aggregates are being used. A project investigating alternatives to primary aggregates, led by the Building Research Establishment (Nixon, 2004), concluded that an alternative could be foamed concrete, which has been widely used for large-scale fills since the early 1990s, as this material has the advantages of self-flowing and levelling, as well as low self-weight properties. However, the project also noted that current technology was compromised by the reliance on Portland cement (PC) only and recommended the development of mixes with lower energy cements or combinations. In response, the present paper describes a research project that investigated the use of high-volume fly ash to reduce the embodied carbon dioxide of ultra-low-density (plastic densities ≤500 kg/m^3) foamed concrete, for application in its most common use as a large-volume fill.

Although many investigations have been conducted on foamed concretes with plastic density of 600–1900 kg/m^3 (Jones and McCarthy, 2005a; Kearsley and Wainwright, 2001; Panesar, 2013; Ramamurthy *et al*., 2009; Wee *et al*., 2011), few studies have been done on ultra-low-density foamed concretes with plastic densities lower than 500 kg/m^3. Chen and Liu (2013) reported an ultra-low-density foamed concrete with plastic density of 400 kg/m^3, which was produced using high-strength PC mixed with expanded polystyrene beads instead of pre-generated foams. Pan *et al*. (2014) and Huang *et al*. (2015) produced ultra-low-density foamed concretes with dry density ≤300 kg/m^3 employing a mixing and foaming process that used hydrogen peroxide as a chemical foaming agent. To produce a stable product, accelerators, thickening agents, foam stabilisers and polymer fibres were added into the fresh mixtures. The products exhibited very low thermal conductivity and desirable strength. Studies on ultra-low-density foamed concrete produced by means of a pre-foaming process have not been found.

Differently from the material used in structural applications (Jones and McCarthy, 2005a), ultra-low-density foamed concrete has found wide applications for thermal or sound insulation, dead load reduction, void filling, and so on, instead of any mechanical purpose.

Research significance

With conventional foamed concrete, the achievement of ultra-low densities is problematic owing to the onset of instability (Pan *et al*., 2014). In a previous paper (Jones *et al*., 2016a), the authors described the underlying principles that promote either stability or instability in foamed concrete. The analysis hypothesised that conversion from a 'liquid' to a 'solid' material within 20 to 30 min from mixing and placing was the key to producing stable, ultra-low-density foamed concrete. This research also described a potential method to achieve this and a successful laboratory-scale demonstration using a small addition (10% of the cement content) of a calcium sulfoaluminate (CSA) cement, which achieved 'solidification' prior to the onset of instability.

In response to the challenge to minimise the PC content in foamed concrete, the research described here builds on the previous work and the aim was to replace as much PC as possible by maximising the use of fly ash in a PC/CSA/fly ash ternary cement system, with a specific focus on minimising embodied carbon dioxide and describing the main characteristics of the resulting material.

With the above approaches, high-volume, ultra-low-density fly ash foamed concrete with low embodied carbon dioxide has been successfully produced using conventional pre-foaming technology by adding a small addition of CSA to achieve stability.

Experimental details

The mix design series was aimed, in this case, to minimise embodied carbon dioxide, and the PC was replaced on a mass for mass basis with fly ash at levels of 30 up to 70% for foamed concrete mixes with volumes of foam adjusted to yield plastic densities from 150 to 500 kg/m^3. In all cases, no aggregate or filler was used. CSA replaced 10% of the total cement content, that is, PC/CSA/fly ash ternary mixes to produce stable mixes, as it had been previously shown that, beyond this level of replacement, an unacceptably fast setting time of the base mix was caused, prior to the addition of foam. A 'conventional' group of cements was selected for simplicity and potential industrial scale-up, rather than an 'alkali-activated' route.

The flow behaviour, stability and bubble structure of the resulting ultra-low-density foamed concrete were characterised and the embodied carbon dioxide was calculated to assess the benefits in terms of sustainability.

Constituent materials

The following constituent materials were used to produce foamed concrete mixes for testing; the main properties of these cements are given in Table 1

- CEM I 52,5N (PC) conforming to BS EN 197-1 (BSI, 2011)
- commercially available CSA cement designed to be used with PC to control setting times; note that this particular CSA did not require any further sulfate source to be added, once mixed with the PC
- two types of fly ashes, FA1 and FA2, conforming to BS EN 450-1 (BSI, 2012), with loss on ignition (LOI) Category A; while FA1 conformed to fineness Category N, FA2 was processed to increase its fineness to 7·5% retained at 45 μm and >85% of the particles less than 25 μm, and hence conformed to the finer Category S (the latter normally being used to 'replace' PC)
- surfactant (commercially available protein-based foaming agent), used in a 6% aqueous solution and foamed to a density of 50 kg/m^3.

Table 1. Cement properties and their embodied carbon dioxide

			Fly ash	
	PC	CSA	FA1	FA2
Main oxides: % by mass				
Calcium oxide (CaO)	66·7	36·9	3·9	5·1
Silicon dioxide (SiO_2)	19·9	4·6	50·1	58·7
Aluminium oxide (Al_2O_3)	4·8	47·2	23·4	21·2
Sulfur trioxide (SO_3)	2·7	5·4	2·4	0·5
Iron (III) oxide (Fe_2O_3)	3·1	1·5	11·4	6·8
Magnesium oxide (MgO)	1·1	1·1	1·4	1·7
Potassium oxide (K_2O)	0·7	0·5	3·3	2·2
Sodium oxide (Na_2O)	0·3	0·1	2·3	1·6
Loss on ignition	—	—	4·0	2·2
Phase and mineralogical composition: % by mass				
C_3S	54·1	—	—	—
C_2S	16·6	19·3	—	—
C_3A	10·8	6·7	—	—
C_4AF	9·1	—	—	—
Ye'elimite	—	52·9	—	—
C_2AS	—	17·5	—	—
Quartz	—	—	11·1	15·3
Mullite	—	—	11·0	7·2
Haematite	—	—	2·3	5·7
Glass	—	—	75·4	71·0
Key physical properties				
45 μm sieve retention: %	—	—	13·2	7·5
Specific surface area: m^2/kg	411	502	485	526
Particle density: g/cm^3	3·15	3·00	2·29	2·20
Embodied carbon dioxide: kg CO_2/t (MPA, 2015)	913	822	4	4

The test mix constituent proportions are given in Table 2. The mix design method developed in a previous study (Jones and McCarthy, 2005b) was used. In this particular study, the water-to-cement (w/c) ratio was kept constant at 0·50, as it was observed to provide sufficient consistency at most densities with various material combinations and the highest strength in the solid phase. For 500 kg/m^3 density, cement content was 335 kg/m^3, which was reduced to 200 kg/m^3, 133 kg/m^3 and 100 kg/m^3 for 300 kg/m^3, 200 kg/m^3 and 150 kg/m^3 densities, respectively. As the study focused on PC/CSA/fly ash ternary mixes, PC, PC/CSA and PC/fly ash mixes were prepared as references for comparison.

Table 2. Mix constituent proportions for the study

Plastic density: kg/m^3	Cement combination	Cement content: kg/m^3			Water content: kg/m^3	Air volume: %
		PC	CSA	Fly ash (FA)		
500	100PC	335	—	—	165	73
500	50PC/10CSA/40FA	165	35	135	165	71
300	100PC	200	—	—	100	85
300	95PC/5CSA	190	10	—	100	84
300	90PC/10CSA	180	20	—	100	84
300	60PC/10CSA/30FA	120	20	60	100	83
300	50PC/10CSA/40FA	100	20	80	100	83
300	40PC/10CSA/50FA	80	20	100	100	82
300	30PC/10CSA/60FA	60	20	120	100	82
300	20PC/10CSA/70FA	40	20	140	100	82
200	95PC/5CSA	126	7	—	67	89
200	90PC/10CSA	120	13	—	67	89
200	60PC/10CSA/30FA	80	13	40	67	88
200	50PC/10CSA/40FA	67	13	53	67	88
200	40PC/10CSA/50FA	53	13	67	67	88
150	90PC/10CSA	90	10	—	50	92
150	50PC/10CSA/40FA	50	10	40	50	91

Test methodologies

Flow behaviour

The flow of mixes was measured by the modified Marsh cone method (Jones *et al.*, 2003). The flow behaviour is characterised by either flow time per unit volume of foamed concrete or flow volume per unit time. Normally flow time was measured for 1 l efflux for densities above 500 kg/m^3, but this was changed to measure volume of foamed concrete flowed in 5 min for 300 kg/m^3 density or below due to the less flowable nature of the ultra-low-density mixes.

Stability and collapse time

Stability checks were carried out with the method proposed by Jones *et al.* (2016b). Fresh-mixed foamed concrete was cast into dia. 75 × 500 mm cylinders lined with polythene film. The change in the surface level was observed and the drop in level over 24 h was measured as an indicator for stability.

For mixes with density 300 kg/m^3 and below, the samples were observed simply to collapse when instability occurred (Jones *et al.*, 2016a). In this case, the collapse time was recorded, which started from the addition of foam to the base mix and continued until the foamed concrete started to drop in level.

Setting time

As a key parameter for the stability of foamed concrete, as discussed in Jones *et al.* (2016a), determination of setting time was carried out on base mixes of the foamed concretes under consideration. Automatic Vicat apparatus complying with BS EN 196-3 (BSI, 2008) was used for this test.

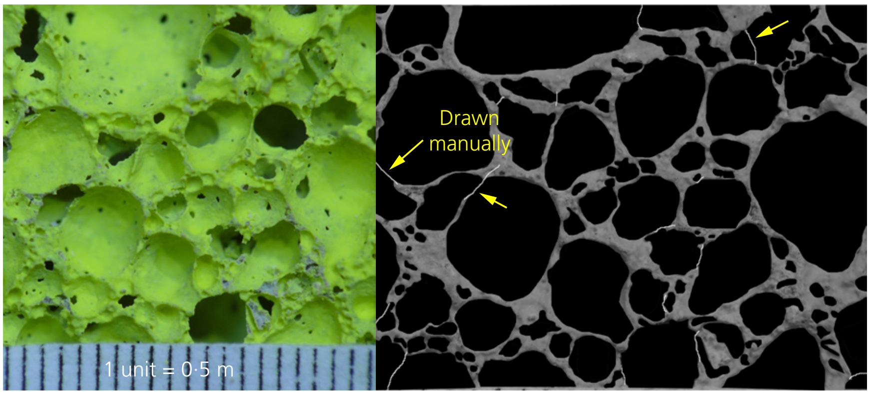
Bubble size and microstructure

Bubble size analysis of the hardened foamed concrete was carried out following a previously developed methodology (Jones *et al.*, 2016a, 2016b; Nambiar and Ramamurthy, 2007). Dia. 75 × 500 mm long cylinder specimens resulting from the completion of the stability test were used. These were laboratory sealed–cured for 28 d and then removed and split longitudinally. Test elements of approximately 75 mm squares sampled from the top, middle and bottom (in the direction of casting) of the cylinder were taken to measure bubble size throughout the specimen. To improve the image contrast under ultraviolet (UV) illumination, the surfaces of the test specimens were sprayed with fluorescent paint. Two-dimensional (2D) image analysis was carried out by widely available open source analysis software (Ferreira and Rasband, 2012) on images of approximately 10 × 10 mm (e.g. Figure 1(a)) from the middle of the test sub-sample. Prior to the image processing, borders of the bubbles were made visible by drawing lines where the borders were not clear in the black and white image, in order to increase the accuracy of the results (Figure 1(b)).

Scanning electron microscopy (SEM) images were used to observationally assess the microstructure of the bubbles (Philips XL30 environmental SEM at 15 kV and sputter coated with 20–30 nm gold/palladium using a Cressington 208HR).

Mechanical and physical properties

As ultra-low-density foamed concretes have very low compressive strength (<1·0 MPa), this was not the main focus of the present study. The test was carried out on 100 mm, 28 d,



(a) (b)

Figure 1. (a) Image for bubble analysis and (b) a processed image in Image J

sealed, cured cubes in accordance with BS EN 12390-3 (BSI, 2009) to provide a guideline for compressive strength values.

In addition, drying shrinkage was determined on 40 mm × 40 mm × 160 mm prisms in accordance with BS EN 680 (BSI, 2005), determination of the drying shrinkage of autoclaved aerated concrete. Thermal conductivity was measured in accordance with the method described in Jones *et al.* (2003).

Results and discussion

Flow behaviour

At ultra-low densities, when the volume of air dominates the solids content, the flow behaviour is controlled by the interaction of the bubbles. The bubbles are closer together due to thinner wall thicknesses and it is likely that their surface charges are sufficiently strong to produce mutual attraction, resulting in a cohesive and less flowable mix, as illustrated in Figure 2.

According to the results obtained from the modified Marsh cone method, neither 200 nor 300 kg/m^3 mixes were self-flowing through the 12·5 mm orifice. Therefore, this method was not suitable for measuring the consistency of mixes below 500 kg/m^3. Given the increased bubble size of the mixes with decreasing density, bubbles tend to block the orifice, interrupting, and hence slowing down the flow. However, these mixes, especially 300 kg/m^3, were observed to flow easily through a scoop when pouring them into the moulds. Even though these mixes were not self-levelling, they were flowing easily and only a minimum of external force was needed to produce a level finished surface. Their flow behaviour may be better evaluated using the inclined-pipe method suggested by Murata and Suzuki (1997).

Jones and McCarthy (2005a, 2005b) and Jones *et al.* (2012) reported that replacing fine aggregates with coarse fly ash at

(a) (b)

Figure 2. Influence of plastic density on the flow behaviour of foamed concrete: (a) 600 kg/m^3 low density; (b) 300 kg/m^3 ultra-low-density foamed concrete

1000 kg/m^3 density enhanced the flow significantly. On the other hand, replacing PC with fine fly ash was found to reduce the flowability of foamed concrete at 1000 kg/m^3 (Jones *et al.*, 2003), given the increased overall specific surface area required to be wetted by the same quantity of added water, resulting in a lower effective free water phase.

Although reduction in flowability was reported when fine fly ash was used as cement replacement, the effect of replacing PC with fine fly ash (FA2) on the flow behaviour of 200 and 300 kg/m^3 densities was evaluated at fly ash levels of 30, 40 and 50% by mass of cement and the results are shown in Figure 3.

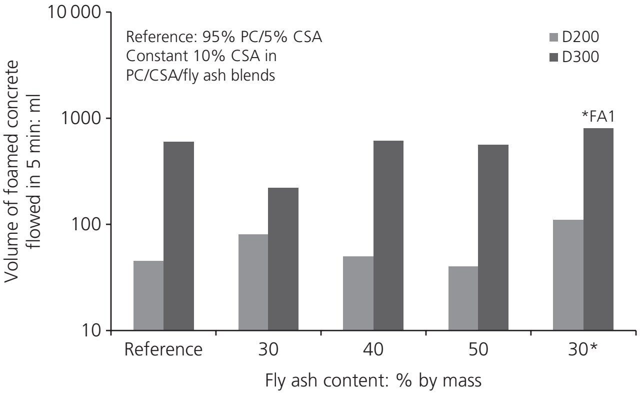


Figure 3. Influence of fly ash FA2 on the flow behaviour of ultra-low-density foamed concretes

As stated earlier, the test method was modified to measure the flow of fly ash mixes so that the efflux obtained in 5 min was recorded. However, the use of fly ash in the 200 and 300 kg/m^3 mixes did not result in a consistent trend of flow behaviour.

Using 30% FA2 by mass of cement reduced the flow of 300 kg/m^3 mix to almost one third of the reference mix, whereas at 200 kg/m^3 flow increased by almost 44%. Unlike FA2, utilisation of 30% FA1 (which is slightly coarser than FA2) improved the flow by 33% and 144% for 300 and 200 kg/m^3 mixes, respectively.

Further increasing the FA2 content up to 40% improved the flow of the 300 kg/m^3 mix slightly, while improving the 200 kg/m^3 mix by 11% in comparison to the reference mix. Utilising 50% FA2 had a negative impact on the flow behaviour of 200 and 300 kg/m^3 with 11 and 6·7% decrease. Overall, the effect of FA2 on the flow behaviour was not significant at 40 and 50% replacement levels. The most significant effect was observed at 30% replacement both in FA1 and FA2 (except for 300 kg/m^3), and FA1 was found to enhance the flow more significantly.

Collapse and initial setting times

PC and PC/fly ash only mixes

As identified previously (Jones *et al.*, 2016a), to prevent instability, the foamed concrete mixes must solidify prior to bubbles coalescing and becoming large enough to become buoyant. This is a time-dependent phenomenon and, therefore, only an initial setting time prior to that point prevents the onset of instability. The stable time period for fresh foamed concrete is variable and depends on many factors, but primarily on plastic density.

Collapse times of the PC and PC/fly ash mixes were measured from the surface drop test, which are given in Figure 4. The data show that fly ash enhanced stability, delaying the onset of instability from 35 to 75 min for densities from 150 to 300 kg/m^3. The fly ash content (30 to 70%) or fineness had no significant effect on this observation. The fly ash content did

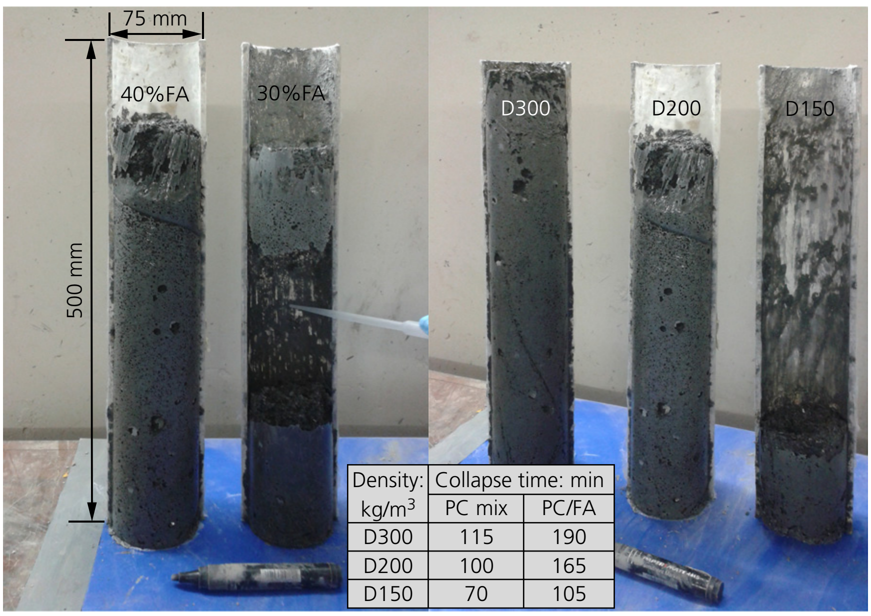


Figure 4. Collapse of ultra-low-density mixes produced with PC and PC/fly ash mixes: (a) drop level of 200 kg/m^3 density foamed concrete with 40% and 30% fly ash; (b) drop level of 300, 200 and 150 kg/m^3 density foamed concrete with 40% fly ash

have an effect on the degree of surface drop as the mixes became unstable (Figure 4(a)), which was lower for the 40% fly ash, 200 kg/m^3 density mixes compared to the 30% fly ash.

This improvement may be due to a denser packing of smaller fly ash particles (Nambiar and Ramamurthy, 2007) surrounding the bubbles, restricting them from expanding and coalescing compared to PC (Jones *et al.*, 2016a). However, this is difficult to confirm and other surface chemistry/charge and rheological effects are also likely to play a role.

Inclusion of 10% CSA mixes

Using 10% CSA produced stable foamed concrete 200 to 300 kg/m^3 densities with up to a 70% fly ash content, without any instance of instability prior to setting. Above a 50% fly ash content there was some retardation of the initial set of the base mix (Figure 5), but this only affected the lowest 150 kg/m^3 density foamed concrete mix and limits the maximum fly ash content to 40%. Although this could be offset by increasing the CSA content above 10%, the base mix was found to set too quickly and prevented the foam from being incorporated into these mixes.

Microstructure

Bubble size analysis

The effect of fly ash on the bubble characteristics of foamed concrete depends on how the fly ash is used, that is, either to replace PC or to replace sand. Replacing PC with fly ash has been reported (Wei *et al.*, 2014) to cause an increase in average bubble size, whereas replacing sand (Nambiar and Ramamurthy, 2007), if used, produces a smaller bubble size. However, it should be noted that these data are for plastic densities well above those reported here and hence not strictly comparable.

Figure 6 shows the relationship of bubble size changes with foamed concrete density and with the addition of CSA and fly

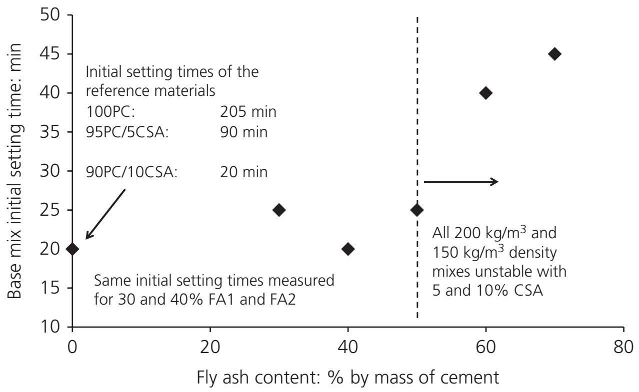


Figure 5. Effect of varying fly ash content on initial setting times of the base mixes containing 10% CSA cement

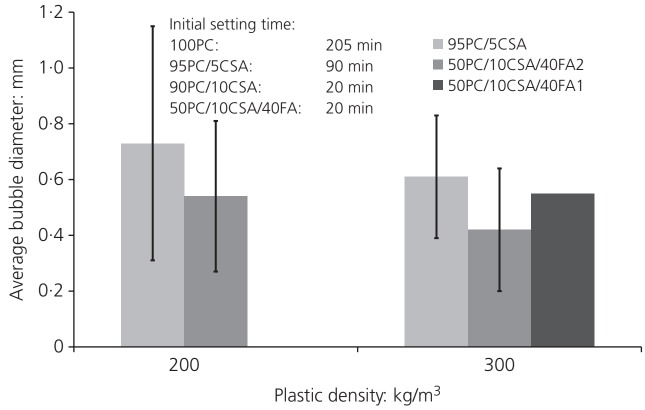


Figure 6. Effect of utilisation of fly ash on average bubble diameter

ash. Generally these data are in line with a previous study (Jones *et al.*, 2016a) at higher density, where the average bubble size was inversely proportional to plastic density. In these tests, the use of fly ash marginally reduced the average bubble size.

When 40% FA2 was introduced in the mix with 10% CSA cement, the combined fineness of the cement blend increases, while the initial setting time decreases from 90 min to 20 min. The combined effect of these significantly reduced the average bubble diameter by 26% and 31% at densities of 200 and 300 kg/m^3, respectively.

In the case of using FA1 instead of FA2, the decrease in the average bubble diameter was found to be slightly less, which may be attributed to the lower specific surface area of the FA1 fly ash. However, as previously noted, other fresh mix characteristics are likely to influence the final bubble size of a particular hardened foam concrete. The measurements of these are beyond the scope of this research.

Comparative microstructural analysis

Given their low solids contents, ultra-low-density foamed concretes with air contents up to 92% (Table 2) have limited strength and a higher porous microstructure. SEM images shown in Figure 7 give a typical range of the bubble microstructures of the test mixes.

The SEM images also show that bubbles occur within the foam bubble walls as well, as shown in Figure 7. These have two distinct shapes, with some being rounded and others ellipsoid. The origins of these bubbles are probably different.

The rounded bubbles are believed to be caused by entrapped air and hence do not have surface charges. This means they are not influenced by the foam bubbles and are thus more stable and unlikely to coalesce.

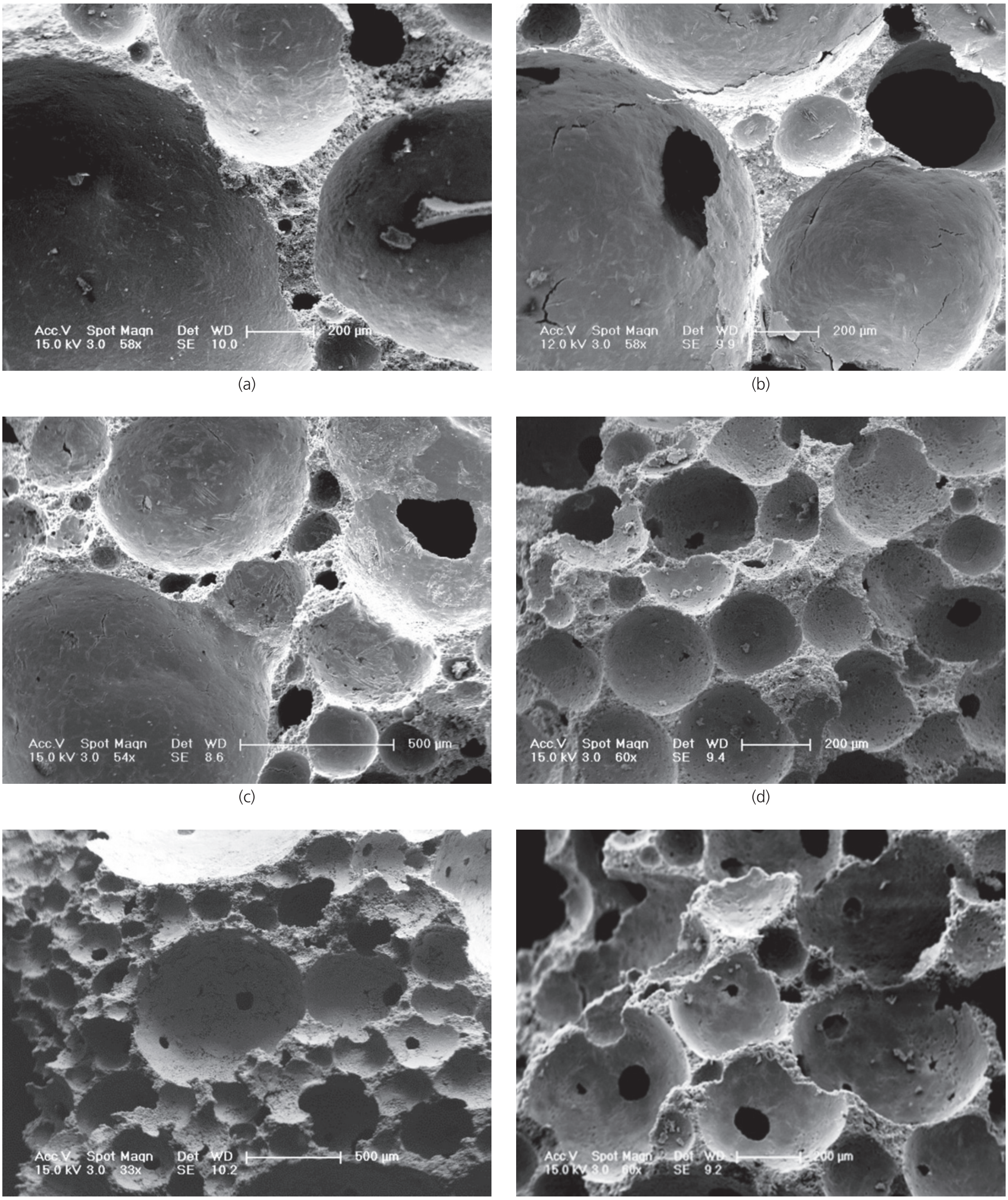
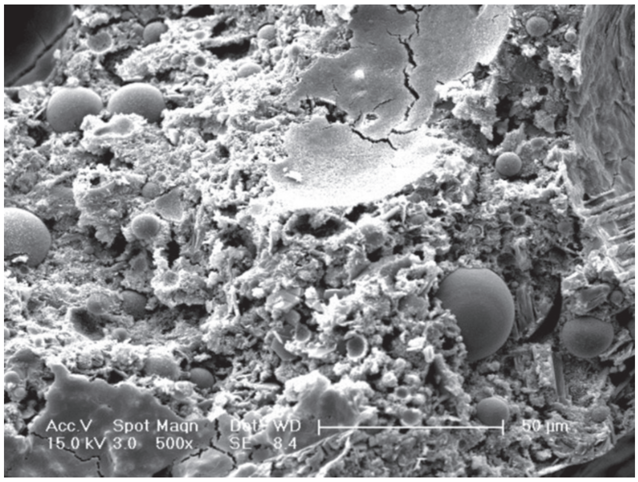


Figure 7. SEM images of 28 d foamed concrete with different densities and fly ash contents: (a) D500-100PC; (b) D300-95PC5CSA; (c) D300-60PC10CSA30FA2; (d) D300-40PC10CSA50FA2; (e) D300-20PC10CSA70FA2; (f) D200-40PC10CSA50FA2

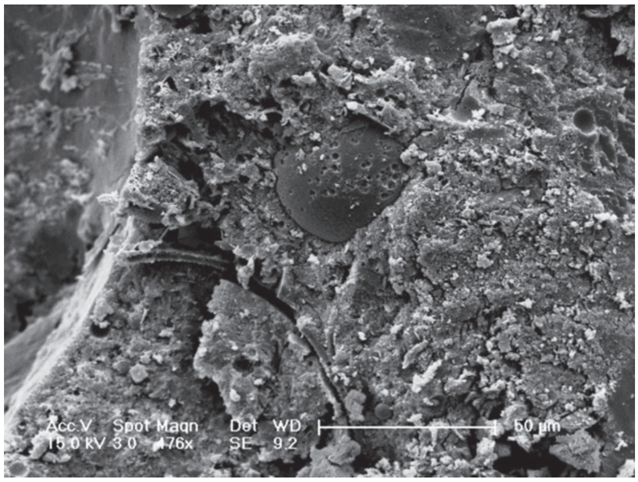
The ellipsoidal bubbles, however, are more likely to be derived from surfactant foam and local forces causing the oval shape. Moreover, these very small bubbles may potentially be the origin of larger bubble size changes using a process akin to Ostwald ripening (Jones *et al*., 2016a). As a result, bubbles that were growing in diameter were left surrounded with these small bubbles in the walls once hardened.

The interior surface texture of these bubble groups is also different. The large bubbles' interiors have smooth surfaces consistent with a foam 'binding' solids to its surface and producing a cement-rich paste layer. The bubbles in the walls tend to show roughened surfaces, whether rounded or ellipsoidal. The large bubbles also often show cracks. Most of these are due to the fracturing of the foamed concrete to prepare the material for SEM and are typified by those which traverse from one bubble to another. However, there are also cracks that terminate within bubbles, and these are most likely to be due to local tensile strain owing to differential drying shrinkage. Although the exact cause or effect is not clear, this does have implications for inter-bubble connectivity and the flow of heat, sound or moisture.

Figure 8 shows the changes in microstructure of a sealed-cured 300 kg/m^3 fly ash mix from 28 d to 13 months. Visually, the walls of this mix appear to densify with age, suggesting that there is sufficient free water available to continue to keep pozzolanically reacting the fly ash. The influence of this long-term behaviour was not part of this research but is likely to be advantageous to both strength and other mechanical properties. At both 8 and 13 months no unreacted fly ash cenospheres are seen, compared with those widely seen at 28 d (the presence of cracks transecting the walls are most likely artefacts of fracturing the sample in preparation for the SEM).



(a)



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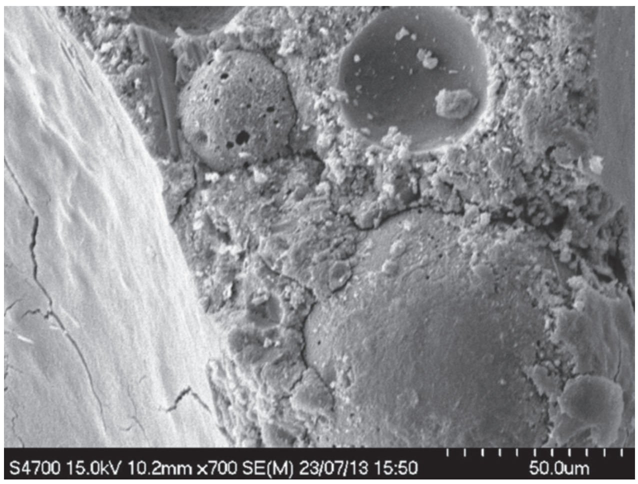

(c)

Figure 8. SEM images of bubble wall of D300-30FA1 foamed concrete at different ages: (a) 28 d; (b) 8 months; (c) 13 months

Mechanical and physical properties

The 28 d cube strength, drying shrinkage and thermal conductivity values of selected ultra-low-density foamed concrete samples are given in Table 3.

The sealed-cured 28 d compressive strength of 500 kg/m^3 foamed concrete ranged from 0·3 to 0·4 MPa, with the fly ash mix higher than the PC mix. The strength of 300 kg/m^3 foamed concrete ranged from 0·2 to 0·25, with the fly ash mix higher than the PC mix again. The addition of 5% CSA also improved strength. No strengths were measured for foamed concretes with density $\leq$200 kg/m^3. The results are lower than those reported by Pan *et al*. (2014) and Huang *et al*. (2015) owing to the difference in the foaming process and the addition of polypropylene fibres in their cases.

Drying shrinkage values were in a similar range around 300 µ-strain for both 500 kg/m^3 and 300 kg/m^3 fly ash mixes, which were much lower than those of the PC and PC/CSA

Table 3. Mechanical and physical properties of ultra-low-density foamed concrete

Plastic density: kg/m^3	Cement combination	28 d cube strength: MPa	28 d drying shrinkage: μ-strain	Thermal conductivity: W/mK
500	100PC	0·31	359	0·18
500	50PC/10CSA/40FA	0·42	310	0·19
300	100PC	0·18	448	0·11
300	95PC/5CSA	0·23	487	0·10
300	90PC/10CSA	—	531	0·11
300	60PC/10CSA/30FA	—	—	0·10
300	50PC/10CSA/40FA	0·25	307	0·11
300	20PC/10CSA/70FA	—	—	0·11
200	95PC/5CSA	≤0·1[a]	—	0·08
200	90PC/10CSA	≤0·1[a]	—	0·08
200	60PC/10CSA/30FA	≤0·1[a]	—	0·07

[a]Strength is lower than the measuring range of the cube crushing machine

mixes. The addition of fly ash reducing the drying shrinkage has also been reported for 1000 kg/m^3 to 1600 kg/m^3 foamed concrete mixes in previous studies (Jones and McCarthy, 2005a; Jones *et al*., 2003).

The thermal conductivity values reduced significantly with a decrease in foamed concrete density; however, no obvious changes were seen for different mixes at the same density level. The values were also significantly lower than that of 1000 kg/m^3 foamed concrete reported in Jones *et al*. (2003). However, no significant reduction effect was observed for the addition of fly ash on thermal conductivity values. This means that, in the ultra-low-density range, the thermal conductivity is mainly determined by the air volume and the characters of the air voids. Small changes in solid components have only a minor effect on thermal conductivity.

Embodied carbon dioxide

As noted previously, a key objective of this work was to reduce and minimise the embodied carbon dioxide content of these

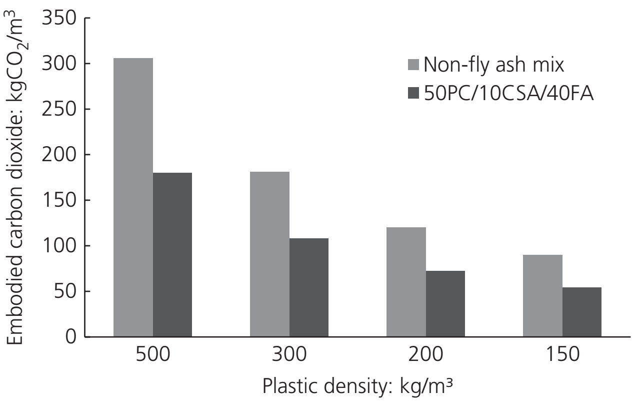

Figure 9. Influence of plastic density and fly ash on the embodied carbon dioxide of foamed concrete

mixes and, because the embodied carbon dioxide contents of the main constituent materials of concrete in the UK have been published, it is possible to enumerate the effect of using high fly ash contents. The embodied carbon dioxide contents of the test mixes were calculated following the method described by CISCF (2008) and the embodied carbon dioxide data of the constituents as published by Mineral Products Association (MPA, 2015) were used. There are no published data for the CSA cement, although, in theory, it is estimated to generate 20–25% less carbon dioxide than PC (Quillin, 2007), and its scale of manufacture is also much lower than PC. Therefore, having consulted MPA, and based on the general assumption that its production energy demand is 10% lower than PC, an embodied carbon dioxide content of 822 kg/t has been used for the CSA in this study.

The embodied carbon dioxide values of foamed concretes with densities ranging from 150 to 500 kg/m^3 produced with non-fly ash and 40% fly ash cement combinations are shown in Figure 9. As the mixes with plastic densities from 600 to 1000 kg/m^3 were designed with fixed cement contents of 300 kg/m^3, which is the dominant factor affecting the embodied carbon dioxide, the embodied carbon dioxide of these foamed concrete mixes are at a similar level and slightly lower than that of the 500 kg/m^3 density PC mix, which has 335 kg/m^3 PC (Table 2).

With the reduction in the densities, embodied carbon dioxide is proportionally reduced. The embodied carbon dioxide of 150 kg/m^3 mixes is about 70% lower in comparison to the embodied carbon dioxide in the corresponding 500 kg/m^3 mixes, mainly owing to their lower cement contents. Further reduction in the embodied carbon dioxide is provided by replacing the PC with fly ash at all density classes proportionally; for example, 40% fly ash replacement provided further 40 to 42% reductions in the embodied carbon dioxide for foamed concretes, with plastic densities ranging from 150 to 500 kg/m^3. Combining both the density reduction and the fly ash replacement effects, and considering the strength factor, 300 kg/m^3 foamed concrete with 40% fly ash resulted in a 65% reduction in the embodied carbon dioxide in comparison with 100% PC 500 kg/m^3 foamed concrete mix. The 28 d strengths of these concretes were 0·25 MPa and 0·31 MPa, respectively.

Conclusions

Using the understanding presented in a previous paper (Jones *et al.*, 2016a), which identified the underlying mechanisms controlling stability and instability on foamed concrete, a high-fly-ash-content (up to 70%), ultra-low density mix has been developed. This requires the use of 10% CSA cement to facilitate rapid setting so as to prevent the onset of instability.

The effect of fly ash fineness did not have a significant effect, which means run-of-station material or even recovered or conditioned materials could be used, with the associated cost and environmental benefits.

In line with the previous study (Jones *et al.*, 2016a), the bubble size of foamed concrete increased with reducing density for the same cement combinations. Decreased bubble diameters in fly ash mixes support the hypothesis that replacing PC with fly ash produces more stable bubbles. The SEM data also support this and show that the bubble size reduced and bubble walls became thicker with the use of fly ash. At densities below 200 and 150 kg/m^3, the fly ash contents had to be limited to 60% and 40%, respectively. It is theoretically possible to increase the level of fly ash, but only by increasing the CSA level. To do this would require short-term retardation of the base mix to allow the foam to be incorporated; the added complication of this procedure was not suitable for the current focus of this research. Fly ash continued to improve the microstructure of foamed concretes up to the age of 13 months, when sealed-cured.

Replacing PC with high volumes of fly ash significantly reduces the embodied carbon dioxide of the mixes. 300 kg/m^3 foamed concrete with 40% fly ash resulted in a 65% of reduction in the embodied carbon dioxide in comparison with 100% PC 500 kg/m^3 foamed concrete mix. Their 28 d strengths were 0·25 MPa and 0·31 MPa, respectively. This can bring significant benefits in sustainable construction large-scale applications, that is, backfill applications.

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